



NATIONAL STEEL AND SHIPBUILDING COMPANY

LEAPFROG TECHNOLOGY TO
STANDARDIZE EQUIPMENT
AND SYSTEM INSTALLATIONS

UNIVERSITY OF NEW ORLEANS SUBCONTRACT

NSRP 0537 PROJECT SP-6-95-2 Sept. 1999

SECTION NO. 5 — ENGINEERING, TESTING, AND VALIDATION METHODOLOGY

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TABLE OF CONTENTS

5.A ESTABLISH ENGINEERING, TESTING, AND VALIDATION METHODOLOGY FOR EQUIPMENT INSTALLATIONS	5-1
METHOD OF ANALYSIS.....	5-2
LOADING.....	5-2
FAILURE CRITERIA	5-3
STRENGTH.....	5-3
FREQUENCY	5-4
ALLOWABLES	5-5
STRESS.....	5-5
FREQUENCY	5-5
FOUNDATION CONFIGURATION	5-5
GRILLAGES.....	5-5
FRAMES/TRUSSES.....	5-7
STUDS	5-7
SPOOLS	5-7
5.B ESTABLISH ENGINEERING AND VALIDATION METHODOLOGY FOR DISTRIBUTIVE SYSTEM INSTALLATION.....	5-7
METHOD OF ANALYSIS.....	5-8
LOADING.....	5-9
FAILURE CRITERIA	5-9
STRENGTH.....	5-9
FREQUENCY	5-10
ALLOWABLES	5-10
STRESS.....	5-10
FREQUENCY.....	5-11
APPENDIX A — SHIP'S MOTIONS ACCELERATIONS	A-1
APPENDIX B — BOLT ATTACHMENT CALCUALTION METHODS.....	B-1
APPENDIX C — GRILLAGE SPREADSHEET CALCULATION METHOD.....	C-1
APPENDIX D — BEND TEST REPORT OF 12" AND 18" PIPE HANGER PROTOTYPES WITH 3/4" AND 1" DIAMETER WELD STUDS.....	D-1
THE TEST	D-2
BEND TEST FIXTURE	D-2
TEST OBSERVATIONS AND COMMENTS	D-2
TEST NO. 1.....	D-2
TEST NO. 2.....	D-2
TEST NOS. 3 AND 4.....	D-2
TEST NO. 5.....	D-2
TEST NO. 6.....	D-2



TEST NO. 7	D-3
TEST NO. 8	D-3



5.A ESTABLISH ENGINEERING, TESTING, AND VALIDATION METHODOLOGY FOR EQUIPMENT INSTALLATIONS

Under this task we have looked at the engineering criteria, specifications and requirements, and the design and fabrication attributes for cost reduction and producibility, and we have framed up an integrated set of procedures to conduct engineering analyses and verification of the standards to be proposed later in the project. This sub-task report describes and outlines this engineering methodology. This section also elaborates the loading criteria, failure criteria and allowable limits to be used in the standards development calculations.

Standard equipment foundations are categorized into 27 representative foundation designs, 18 standard method mounts, Spool mounts and Stud Mounts, as described under sub-task 4.A. The Shipboard Modular Arrangement Reconfiguration Technology (SMART) Systems from Affordability Through Commonality (ATC) for equipment foundation system will also be evaluated and incorporated, as required. The SMART system utilizes a 2-dimensional installation plane incorporating components like parallel tracks, foundation adapters, and foundation sub-assemblies, spread over the area of interest. This provides the equipment installer with the flexibility to install equipment at any orientation and desired location in the area of interest, without needing to design and integrate the foundations with the ship structures. The area of interest can be either decks or bulkheads.

Analysis of the foundation types will be conducted for only certain candidate foundation types. These candidate foundation types are such that, they or variations of them will represent all of the standard foundation types mentioned above. During the course of development of the standards a parametric analysis approach to foundation design will be adopted and used.

Foundation installation statistics reveal that the variety of combinations of geometries and equipment weights is limited and can be clearly defined. Utilization of a parametric analysis approach provides solutions for broad ranges of possibilities at one time, rather than each time the possibility is encountered, which can be drawn upon later to significantly reduce engineering and design time. Standard foundation designs could be developed which satisfy a wide variety of applications. In the final standards development, design data tables and view-graphs for foundations will be included which would allow the engineer to quickly determine if a foundation sketch proposed by the designer is adequate enough by comparison, rather than by performing the detailed analysis for the same scenario repeatedly.

The design data tables of the standards will be generated for commercial applications. In case of naval ships where shock, nuclear blast, noise, and other criteria predominantly govern the foundation design, foundation design validation through standard designs can still be accomplished by performing a parametric approach to foundation analysis and obtaining standard design tables for foundations based on the navy ship requirements and specifications. To validate the initial foundation design the engineer can verify the foundation geometries and scantling sizes with design data tables for adequacy, provided the requirements, specifications and allowables are similar to that used in this standards development. If the requirements and allowables vary then the engineer can scale the foundation geometries and scantling sizes accordingly.

The engineering analysis will be done under four (4) primary categories of foundation/installation, namely

1. Grillages
 - a) Grillage welded to mounting plate
 - b) Grillage lifted off mounting plate
 - c) Overhanging Grillage
 - d) Method Mountings
2. Frames and Trusses
3. Stud Mountings



- a) Single Stud
 - b) Multiple Studs
4. Spool Mountings
- c) Single Spool
 - d) Multiple Spools

METHOD OF ANALYSIS

Allowable weight for a given foundation type will be determined based on a number of different failure criteria, all of which fall into two categories, strength criteria and frequency criteria. Finite Element Models and Spreadsheets will be created to calculate the weight limits based on each criteria for a large envelope of foundation configurations. For each configuration, the lowest allowable weight from the most limiting criteria will be used for that specific foundation. The allowables for each of these criteria are calculated using conservative methods, loads and assumptions as described further.

LOADING

Loads are induced into foundation scantlings through the equipment attachments. Ship's motion loads on the equipment, measured in terms of equivalent static G's, are applied to the equipment and the resultant forces are resolved at the attachments. Acceleration values, based on a worst case scenario, of 3 G's vertical, 1.5 G's transverse and 0.75 G's longitudinal are applied to the equipment simultaneously. Combined with the equipment weight, these accelerations produce forces on the equipment acting in all three directions.

In calculating resultant forces at the foundation attachments the number of attachments/ bolts on the scantling span will not be considered, instead a worst case assumption will be made that each scantling span had only two effective bolts. For example, axial and shear forces will be computed as if there is only one bolt on either scantling of a foundation span. Overturning forces will be computed based on the e/h of the equipment and distributed on the foundation spans as if they are supported by only one bolt. Since forces are acting in three directions, there are two directions which produce overturning forces and in reality two different equipment e/h 's to consider, but to be conservative the minimum of the two values, producing the higher resultant force for a given load, will be used for both directions of overturning. Additionally, the worst conceivable load at the bolt will be calculated by orientating the foundation so that the ship's motion loads produce the highest bolt loads. Figure 5-1 shows the resolved forces for a particular grillage configuration.

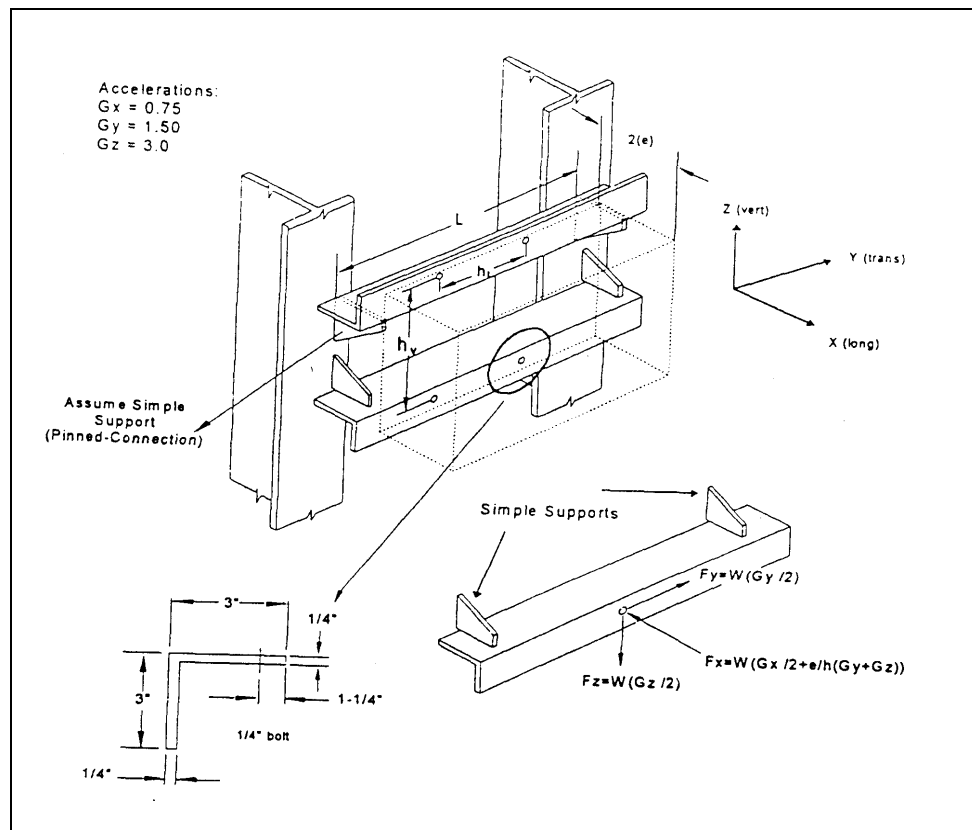


Figure 5-1 — Resolving of Grillage Forces

FAILURE CRITERIA

STRENGTH

Based on the worst foundation configurations and loads, stresses will be computed for all possible failure modes. Failure is assumed to occur through yield failure in one or all of the scantlings, or by local yield failure in way of one or more bolts. All stresses will be computed at their worst location, the spot on the foundation where the biggest force or moment occurs.

Angle stresses will be calculated using beam formulae. Critical stress occurs in a scantling as a result of both bending and axial loads in the beam. Bending stresses will be combined for bi-axial bending, where the stress at the toe of the angle from one direction of bending will be added to the stress at the heel from the other direction of bending and vice-versa. This worst bending stress will then be combined with the nominal axial stress calculated from the highest axial load in the foundation scantling/angle and the corresponding cross-sectional area.

Figure 5-2, shows graphically the various local attachment failure criteria. Bolt attachment will be checked for all modes of shear, bearing and bending. All calculations will be performed assuming 1/4" bolts, because this is the smallest bolt size any equipment would generally need and smaller bolts produce higher stresses for all failure modes. Shear failure can either occur perpendicular to the angle flange due to axial bolt loads or parallel to the flange from shear loads in the bolt. Bearing stress is a nominal stress computed from the cross-sectional area of the bolt hole.

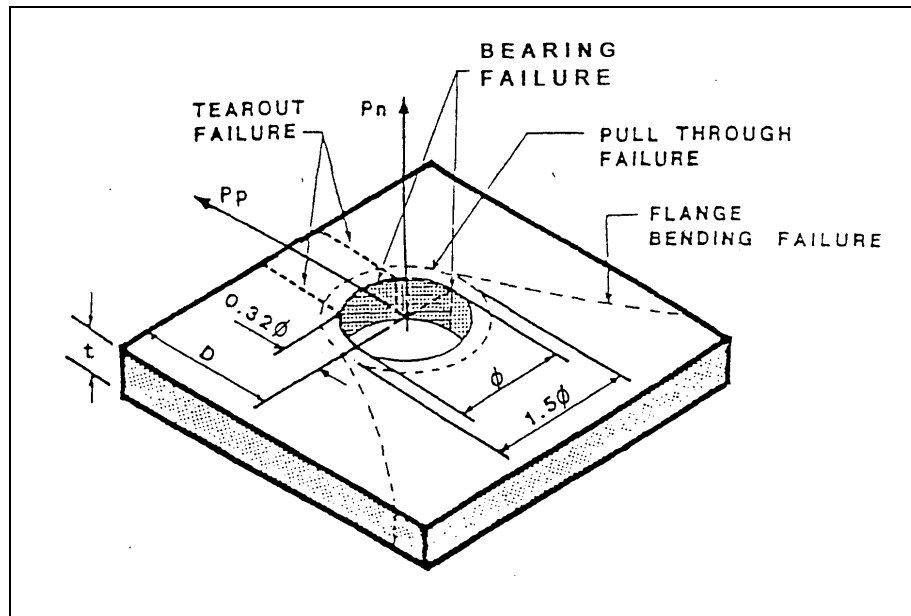


Figure 5-1 — Foundation Bolting Plate

where, P_n	=	Bolt load normal to the plate
P_p	=	Bolt load parallel to the plate
t	=	plate thickness
ϕ	=	Bolt diameter
D	=	Edge distance

Flange bending is the result of the moment created between the centerline of a bolt and the heel of the angle. The greater the bolt distance from the heel, the greater the flange bending moment. So to be conservative, the bolt will be assumed to land at its furthest possible location from the heel i.e. approximately 35 to 40% of the flange width from the toe of the angle. The moment produced is resisted partially at the bolt and partially at the angle heel depending on the condition of fixity at those locations. The most conservative assumption for moment distribution will be assumed, which is when the equipment is always clamped to the flange at the bolt and the heel is partially free, putting 80% of the moment at the bolt and 20% at the heel.

FREQUENCY

For all foundations, it is important to insure that the lowest natural frequency of vibration of the foundation is greater than the excitation frequency of the propeller. The natural frequency will be checked for several modes of vibration, and the lowest natural frequency of the foundation will be compared to the allowable frequency. Springs included in the natural frequency calculation for a foundation are the bending of the scantling, in two directions, and the flexibility of the flange. Torsion flexibility of the mounting scantlings will be disregarded because of the assumption that the flange is clamped to the equipment. Three different vibration modes will be calculated for foundations, i.e. parallel to the mounting plane, perpendicular to the mounting plane, and due to over-turning motion of the equipment.

When a foundation does not fully land on rigid ship structure, it is necessary to check the natural frequency of the foundation coupled with the vibration of the mounting plate. It is no longer necessary



to include the angle as a spring in the vibration calculation, thus the springs for this natural frequency calculation will be the flange flexibility and the out-of-plane bending of the mounting plate. The natural frequency will be calculated for the perpendicular and over-turning modes of vibration.

ALLOWABLES

STRESS

The stress allowables are based on the assumptions that scantlings are of mild steel and studs are of high strength steel, having yield strength and tensile strength of 34 KSI and 50 KSI, respectively.

NOMINAL TENSILE STRESS ALLOWABLE IS 80% OF YIELD STRENGTH	27.2 KSI
SHEAR STRESS ALLOWABLE IS 60% OF TENSILE ALLOWABLE	16.3 KSI
BEARING STRESS ALLOWABLE IS 80% OF TENSILE ALLOWABLE	21.8 KSI
STRESS ALLOWABLE FOR STUDS IS 60% OF TENSILE STRENGTH	30.0 KSI

FREQUENCY

Based on the propeller excitation frequency of 12 Hz, which is found mostly in vessels of higher speeds, the allowable natural frequency for the foundations is kept 25% higher than the propeller excitation frequency. Thus, the allowable frequency to be used to obtain the values in design data tables will be 15 Hz.

FOUNDATION CONFIGURATION

GRILLAGES

Three different types of grillage configurations will be considered for the calculations, namely: Grillage welded to mounting plate; Grillage lifted off mounting plate; Overhanging Grillage. Method Mountings are extensions or combinations of these three primary configurations. The allowable weights for the standards will be obtained using a spreadsheet approach to check for the various failure criteria for 6 different angle sizes, for 2 cases of e/h ratios. Figure 5-3 shows the Grillage Off-deck and Overhanging Grillage configurations.

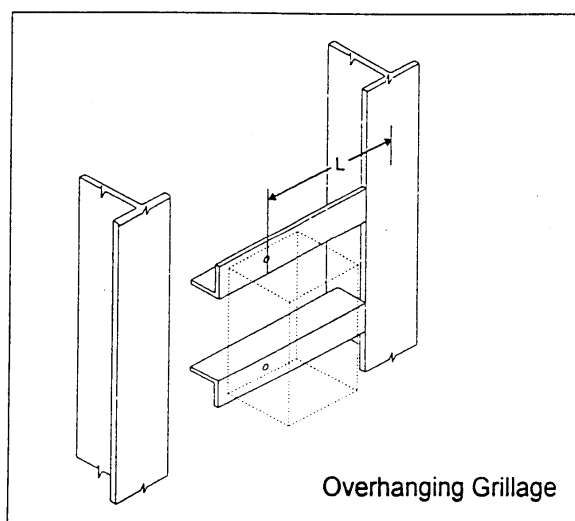
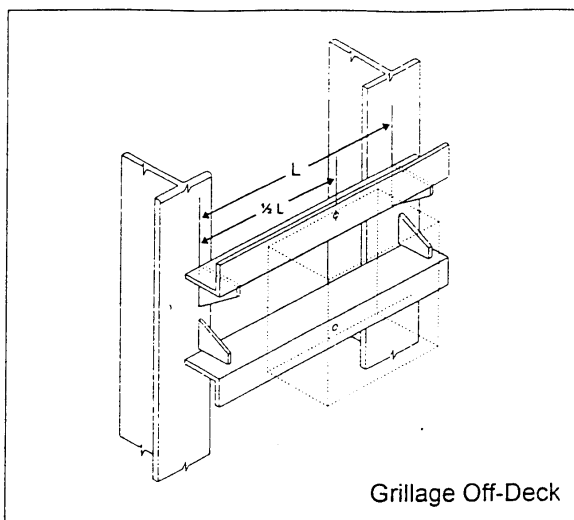


Figure 5-1 — Grillage Off-deck and Overhanging Grillage Configurations



FRAMES/TRUSSES

Various configurations of Frames and Trusses will be analyzed using finite element models (FEM) for 5 different angle sizes, for 2 cases of e/h ratios. The FEMs will be run for the worst combination of G loadings, and the effect of overturning of equipment will also be included. All the models will be of 4 equal size legs, and the mounting attachments (bolt locations) will be assumed to be at the four corners of the mounting plane. The results of FEMs will be used to obtain the allowable weight capacity for the legs of the frames and trusses. A Grillage spreadsheet approach will be used to obtain the allowable weights for mounting scantlings.

STUDS

Studs of various lengths and sizes varying from 5/16" to 3/4" will be analyzed using a spreadsheet approach, to obtain the allowable weight capacities. The worst combination of G loading on two configurations will be analyzed, namely: single stud, and multiple studs (4 studs). In the case of single stud configuration, the varying stand off length is considered from the base of the stud to the C.G. of the equipment, thus taking equipment overturning into consideration. Whereas, for the multiple stud configuration the varying stand off length is the actual stud length, and the equipment overturning is assumed to be restrained.

Both vibration and strength limiting criteria will be checked. Under vibration, frequency due to out-of-plane mounting plate bending, and frequency due to stud and stud/plate connection bending will be checked. Under strength limitation, studs by themselves will be checked for axial plus bending stresses. Further, the stud/plate connection will be analyzed using Roark's equation ("Roark's Formula for Stress and Strain", Warren C. Young, 6th edition, pg. 435, 1989), using various plate thickness.

SPOOLS

Spools of sizes 2.5" and 4" dia. with various lengths will be analyzed using a spreadsheet approach, to obtain the allowable weight capacities. Spools of varying lengths can be obtained by connecting multiple spools end-to-end till the desired length is obtained. The analysis methods described for studs will also be used for spools. In addition to the strength and frequency calculations mentioned for the studs, strength adequacy checks for the spools themselves will also be performed.

5.B ESTABLISH ENGINEERING AND VALIDATION METHODOLOGY FOR DISTRIBUTIVE SYSTEM INSTALLATION

The first step in deriving an engineering methodology or analysis method is to review the engineering criteria and design and fabrication attributes from the previous section. After further review of several of the cost reducing and producibility measures, an analysis plan was formulated. The end result of the engineering should result in a system highly conducive to an automated hanger selection process for pipe, electrical, and HVAC/duct disciplines. This sub-task report describes and outlines this engineering methodology. This section also elaborates the loading criteria, failure criteria and allowable limits to be used in the standards development calculations.

The initial goal of the analysis is to develop a set of tables, charts, or spreadsheets from which a hanger type and size can be selected given a string of input data. The available hanger type and size will be chosen from a distilled list of appropriate, cost saving, and producible hangers. This table of candidate hangers will be assembled as the engineering analysis moves forward.

A logical solution to the above goals would be to achieve a parametric spread of variables for each selected hanger type. Each chosen variable will have an acceptable range for that particular hanger type and size. For instance, a hanger may be able to support anywhere from 1 to 40 Lbs. and has a standoff distance from 1 to 6 inches. The initial variables for which parametric ranges will be implemented are:

- Pipe/cable size



- Pipe/cable weight
- Weight of valves, fittings, etc.
- # of pipes/cables
- Standoff distance
- Hanger spacing

Given the above input criteria for a given system, it is a simple task for a designer to choose a hanger that satisfies the conditions. In some cases, more than one hanger may be acceptable for a certain situation. If this happens, a secondary set of criteria will be considered. This criteria will involve cost factors, producibility factors, and location factors. Thus, a hanger, which is more conducive to a particular area and more cost effective, can be used.

These parametric ranges will define and make-up design data tables which will be part of the installation standards. The ranges will be produced by a variety of engineering methods. For existing hanger types, the ranges will be determined by utilizing existing standards and vendor furnished information. For new and innovative hangers, the ranges will result from a combination of hand calculations, spreadsheets, and some limited FEM analysis. This analysis will also validate the new standards. These design data tables will be developed for commercial applications, and will be comprised of pipe hangers, electrical hangers, and HVAC/duct hangers.

METHOD OF ANALYSIS

The detailed analysis will begin by choosing a collection of core candidates for electrical, piping, and HVAC components. As each iteration takes place, this initial list may be altered and updated. As the process continues, innovations in design can be applied and possibly adopted depending on results. The final compilation will be an acceptable list of new standards. The envisioned analysis effort will be both for a static case and a dynamic or modal case. In addition, the work will be further broken out to look at the case of a single hanger supporting a point load and the case of multiple hangers supporting a rigid pipe or a series of cables acting in unison.

The static case will look at the hangers' capability of supporting weight. Standoff will be a major variable, as the loads will have all three directional components. In the static cases, close attention will be paid to the attachment techniques and strength. Here it will be determined, on a case by case basis, whether a hot weld attachment or a cold pre-outfit method mount / fastener is preferable. These results balanced with cost savings and producibility could define a new manufacturing and installation procedure.

The dynamic or modal analysis will look more at resulting system stiffness and corresponding frequency. Care will be taken to avoid frequencies that coincide with blade rate or reciprocating machinery. The different frequencies produced by rigid pipe and non-rigid cableways will both be considered. This quasi-static approach assuming linear elastic behavior will be used to solve what is essentially a non-linear problem, and will obtain results that are fairly conservative. This analysis will be performed using both spreadsheets and FEA software.

Allowable weight for a given installation type will be determined based on a number of different failure criteria, all of which fall into two categories, strength criteria and frequency criteria. Finite Element Models and Spreadsheets will be created to calculate the weight limits based on each criterion for a range of core installation configurations. For each configuration, the lowest allowable weight from the most limiting criteria will be used for that specific installation. The allowables for each of these criteria are calculated using conservative methods, loads and assumptions as described further.



LOADING

Loads are induced into installation scantlings through the system attachments. Ship's motion loads on the system runs, measured in terms of equivalent static G's, are applied to the system and the resultant forces are resolved at the attachments. Acceleration values, based on a worst case scenario, of 3 G's vertical, 1.5 G's transverse and 0.75 G's longitudinal are applied to the system simultaneously. Combined with the weight of the system along with the fluid its carrying, these accelerations produce forces on the system run acting in all three directions.

In calculating resultant forces at the installation attachments, a worst case assumption of the number of effective bolts will be made. Additionally, the worst conceivable load at the bolt will be calculated by orientating the installation so that the ship's motion loads produce the highest bolt loads.

FAILURE CRITERIA

STRENGTH

Based on the worst installation configurations and loads, stresses will be computed for all possible failure modes. Failure is assumed to occur through yield failure in one or all of the scantlings, or by local yield failure in way of one or more bolts. All stresses will be computed at their worst location, the spot on the installation where the biggest force or moment occurs. Angle stresses will be calculated using beam formulae. Critical stress occurs in a scantling as a result of both bending and axial loads in the beam.

Figure 5b-1, shows graphically the various local attachment failure criteria. Bolt attachment will be checked for all modes of shear, bearing and bending. All calculations will be performed assuming the smallest of the allowed bolts, because smaller bolts produce higher stresses for all failure modes. Shear failure can either occur perpendicular to the flange due to axial bolt loads or parallel to the flange from shear loads in the bolt. Bearing stress is a nominal stress computed from the cross-sectional area of the bolt hole.

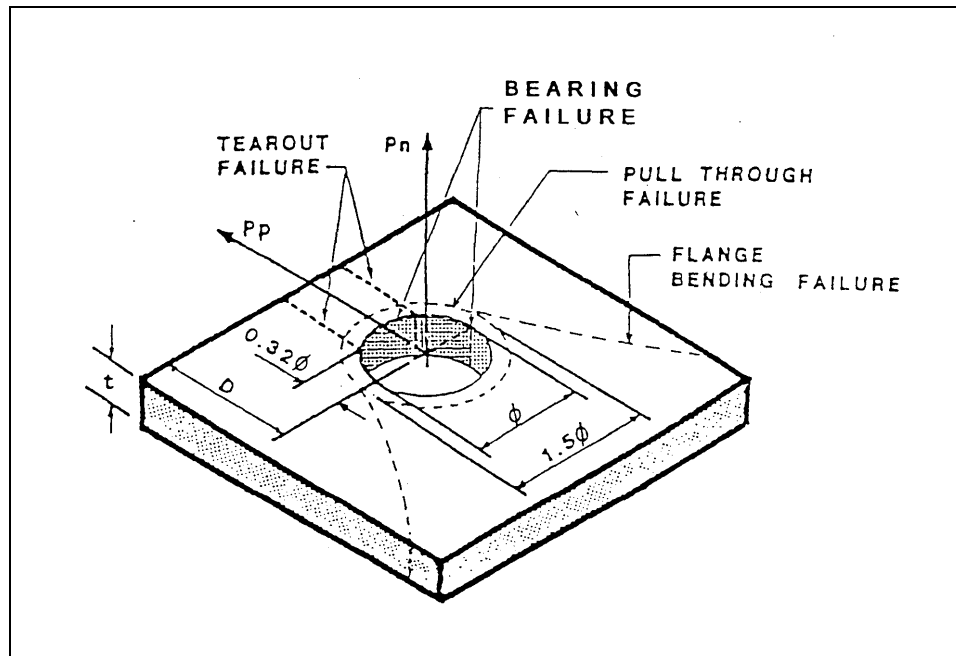


Figure 5-1 — Installation Boring Plate

where, P_n	=	Bolt load normal to the plate
P_p	=	Bolt load parallel to the plate
t	=	plate thickness
ϕ	=	Bolt diameter
D	=	Edge distance

FREQUENCY

For all installations, it is important to insure that the lowest natural frequency of vibration of the installation is greater than the excitation frequency of the propeller. The natural frequency will be checked for several modes of vibration, and the lowest natural frequency of the installation will be compared to the allowable frequency. Springs included in the natural frequency calculation for a system installation are the bending of the scantling, in two directions, and the flexibility of the stiffener flange or deck/bulkhead plating. Torsion flexibility of the stand-off / downcomer scantlings will also be included. For multiple hangers, the asymmetric vibration mode that gives the lowest natural frequency will be calculated first, then higher modes will be checked into.

When an installation does not fully land on rigid ship structure, it is necessary to check the natural frequency of the installation coupled with the vibration of the deck/bulkhead plating. The springs for this natural frequency calculation will be the clamp flexibility and the out-of-plane bending of the mounting plate.

ALLOWABLES

STRESS



The stress allowables are based on the assumptions that scantlings are of mild steel and studs are of high strength steel, having yield strength and tensile strength of 34 KSI and 50 KSI, respectively.

NOMINAL TENSILE STRESS ALLOWABLE IS 80% OF YIELD STRENGTH	27.2 KSI
SHEAR STRESS ALLOWABLE IS 60% OF TENSILE ALLOWABLE	16.3 KSI
BEARING STRESS ALLOWABLE IS 80% OF TENSILE ALLOWABLE	21.8 KSI
STRESS ALLOWABLE FOR STUDS IS 60% OF TENSILE STRENGTH	30.0 KSI

FREQUENCY

Based on the propeller excitation frequency of 12 Hz, which is found mostly in vessels of higher speeds, the allowable natural frequency for the installations is kept 25% higher than the propeller excitation frequency. Thus, the allowable frequency to be used to obtain the values in design data tables will be 15 Hz.

The initial core list of electrical hangers include the following types:

- Nelson Stud
- CH Type
- L Type
- Honeycomb Bulkhead Hanger
- Tubular Hangers (with and without channel support)
- Crosstiers on Channel Downcomers
- Trapeze Type Crosstiers and Cable Troughs
- Flatbar U-bracket

The initial core list of Pipe hangers include the following types:

- U-Bolt Assembly
- U-Bolt Assembly w/ Stan-off or Stool
- Clamp Hangers
- Clamp and Channel Hangers
- Full Cap /Band Hangers
- Single Leg "L" Band Hanger
- RTD Stud Hangers



- Nelson Type Hangers
- Rubber Block Hangers


The initial core list of Ventilation/Ducting hangers include the following types:

- Angle / Flat Bar Down-Corner Hangers
- Angle / Flat Bar Down-Corner w/Clamps Hangers
- RTD Duct Hangers
- Resilient Duct Hangers



APPENDIX A — SHIP'S MOTIONS ACCELERATIONS
--



VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: <u>Dynamic Load Calculations</u>		CALC. BY <u>SLJ</u>	DATE <u>8/15/95</u>
		PROJECT <u>95-040</u>	SHT <u>1</u> OF <u>1</u>

Dynamic Loads Calc. Assume $x = 400'$
from SLNC Ship Specification $y = 45'$
 $z = 60'$

Vertical: (Light)

$$G's = 1.0 + .2 + .0017(x) + .0037(y)$$
$$= 1.0 + .2 + .0017(400) + .0037(45)$$
$$= 1.0 + .2 + .68 + .167 = \underline{\underline{2.05}}$$

Transverse: (Light)

$$G's = .52 + .00084(x) + .002(y) + .0037(z)$$
$$= .52 + .00084(400) + .002(45) + .0037(60)$$
$$= .52 + .336 + .09 + .222 = \underline{\underline{1.17}}$$

Longitudinal:

$$G's = .19 + .00015(x) + .0017(z)$$
$$= .19 + .00015(400) + .0017(60)$$
$$= .19 + .06 + .102 = \underline{\underline{.352}}$$


To be conservative Use:

$$G_v = 2.5$$
$$G_T = 1.25$$
$$G_L = 0.5$$

Figure 5-1 — Dynamic Load Calculations

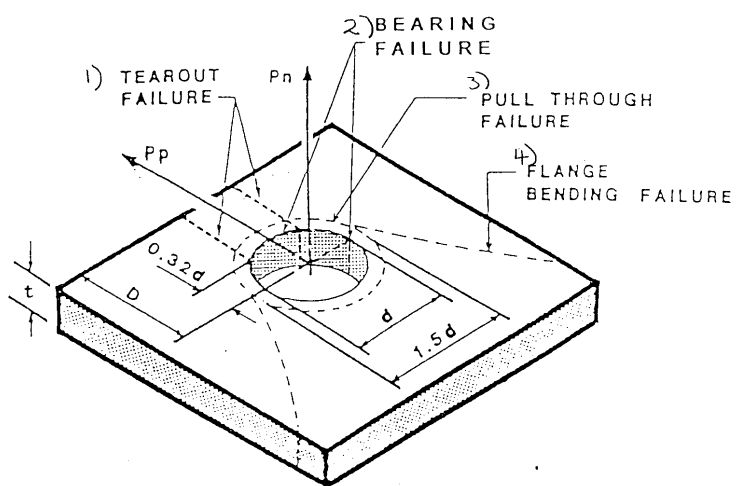


APPENDIX B — BOLT ATTACHMENT CALCUALTION METHODS

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: <u>Bolt Attachment</u> <u>Calculation Methodology</u>		CALC. BY <u>SLJ</u>	DATE <u>8/15/95</u>
PROJECT <u>95-040</u>		SHT <u>1</u> OF <u>11</u>	

There are 4 potential failure modes on the flange in way of the bolts.

SKETCH SHOWING 4 MODES OF FLANGE FAILURE



FOUNDATION BOLTING PLATE

P_N = bolt load normal to the plate

P_P = bolt load parallel to the plate

t = plate thickness

d = bolt diameter

D = edge distance

Figure 5-1 — Four Modes of Flange Failure

VIBTECH, INC.		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>2</u> OF <u> </u>

Shear Tearout Calc. Method:

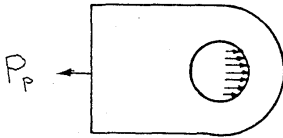


Fig. a

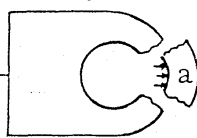


Fig. b

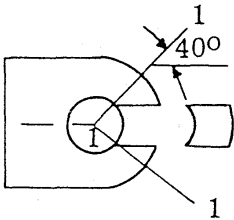



Fig. c

$$\tau_{\text{Tearout}} = \frac{P_p}{A_{\text{shear}}}$$

$$A_{\text{shear}} = 2(D - 0.32d) +$$

$$\tau_{\text{Tearout}} = \frac{P_p}{2(D - 0.32d) +}$$

Figure 5-2 — Shear Tearout Calculation Method

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>3</u> OF _____

Bolt Bearing Calc. Method :

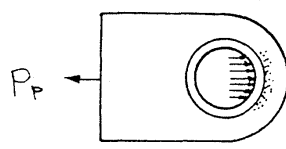


Fig. a

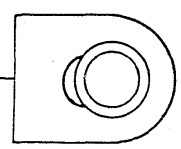


Fig. b


Fig. D1.10

$$\sigma_{\text{Bear}} = \frac{P_p}{A_{\text{Bear}}}$$

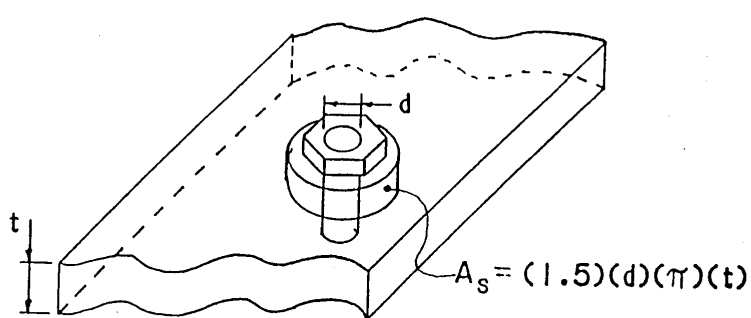
$$A_{\text{Bear}} = d \cdot t$$

$$\sigma_{\text{Bear}} = \frac{P_p}{d \cdot t}$$

Figure 5-3 — Bolt Bearing Calculation Method

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>4</u> OF _____

Bolt Pull Through Calc. Method:




$A_s = (1.5)(d)(\pi)(t)$

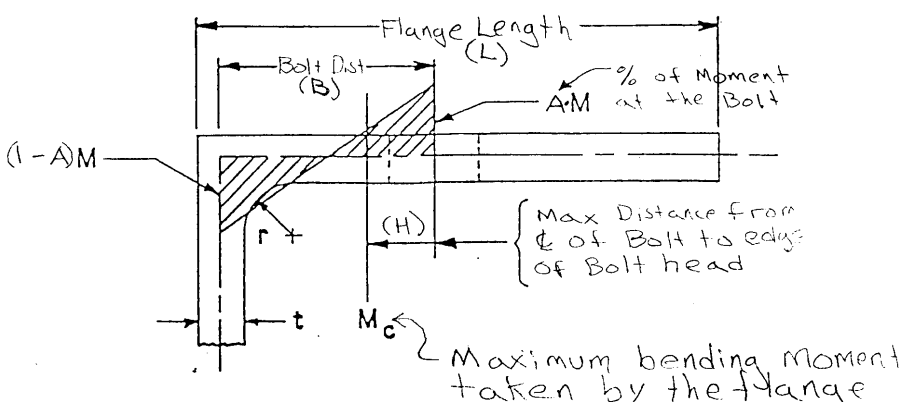
$$\tau_{\text{Pull Through}} = \frac{P_N}{A_s}$$

$$\tau_{\text{Pull Through}} = \frac{P_N}{1.5 d \pi t}$$

Figure 5-4 — Bolt Pull Through Calculation Method

VIBTECH, INC. 	CALCULATION NO. _____	
TITLE: _____ _____	CALC. BY _____	DATE _____
_____	PROJECT _____	SHT <u>5</u> OF _____

Flange Bending Calc. Method:



$M = P_n \cdot B$

Ratio the moment arms to get the critical moment (M_c) at the bolt head edge.

$$\frac{M_c}{A \cdot B - H} = \frac{A \cdot M}{A \cdot B}$$

$$M_c = \frac{(A \cdot B - H)}{A \cdot B} M = \frac{(A \cdot B - H)}{A \cdot B} A \cdot P_n \cdot B$$

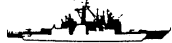
$$M_c = P_n (A \cdot B - H)$$

This moment can be used to calculate a nominal flange bending stress.

$$\sigma_{\text{flange}} = \frac{M_c}{Z}$$

To determine Z , it is necessary to find the length of flange which is effective in bending.

Figure 5-5 — Flange Bending Calculation Method

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>6</u> OF ____

Determine the portion of the flange that is effective in bending:

$$\sigma_{Bnd Flg} = \frac{M_c}{Z}$$

$M_c = P_n(0.5B - H)$, for a flange with clamping at the heel ($A = 0.5$).

$$Z = \frac{I}{Y}$$

$I = \frac{bh^3}{12} = \frac{(XF)(t^3)}{12}$ where X is the effective portion of the flange

$Y = \frac{t}{2}$

$$Z = \frac{\frac{(XF)t^3}{12}}{\frac{t}{2}} = \frac{XFt^2}{6}$$

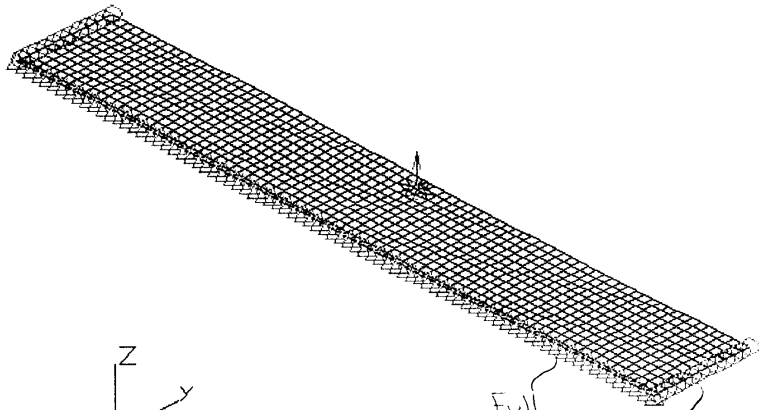
$$\sigma_{Bnd Flg} = \frac{6 \cdot P_n(0.5B - H)}{XFt^2}$$

Using finite element models it is possible to determine the stress at the bolt and the plug this into the equation above in order to solve for X .

$$X = \frac{6 P_n(0.5B - H)}{\sigma_{(from Model)} F t^2}$$

Finite element models were created for different flange bending cases to determine an X applicable to all bolt critical flange bending cases.

Figure 5-6 — Sheet 6 of 11

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>7</u> OF ____

Finite Element Model Details:

3" Flange: 0.25" thick
 Bolt 2.825" from the heel
 $F = 3"$
 $B = 2.5"$
 $t = 0.25"$
 $P_n = 1000 \text{ lbs.}$
 $H = 0.1875"$

Typical Algor Flange Bending Model
 Fully Fixed at the heel; Simply Supported at the ends

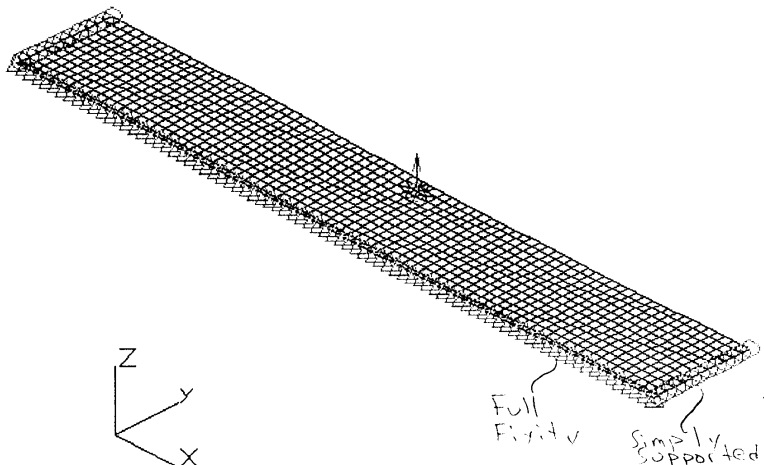


Figure 5-7 — Finite Element Model Details

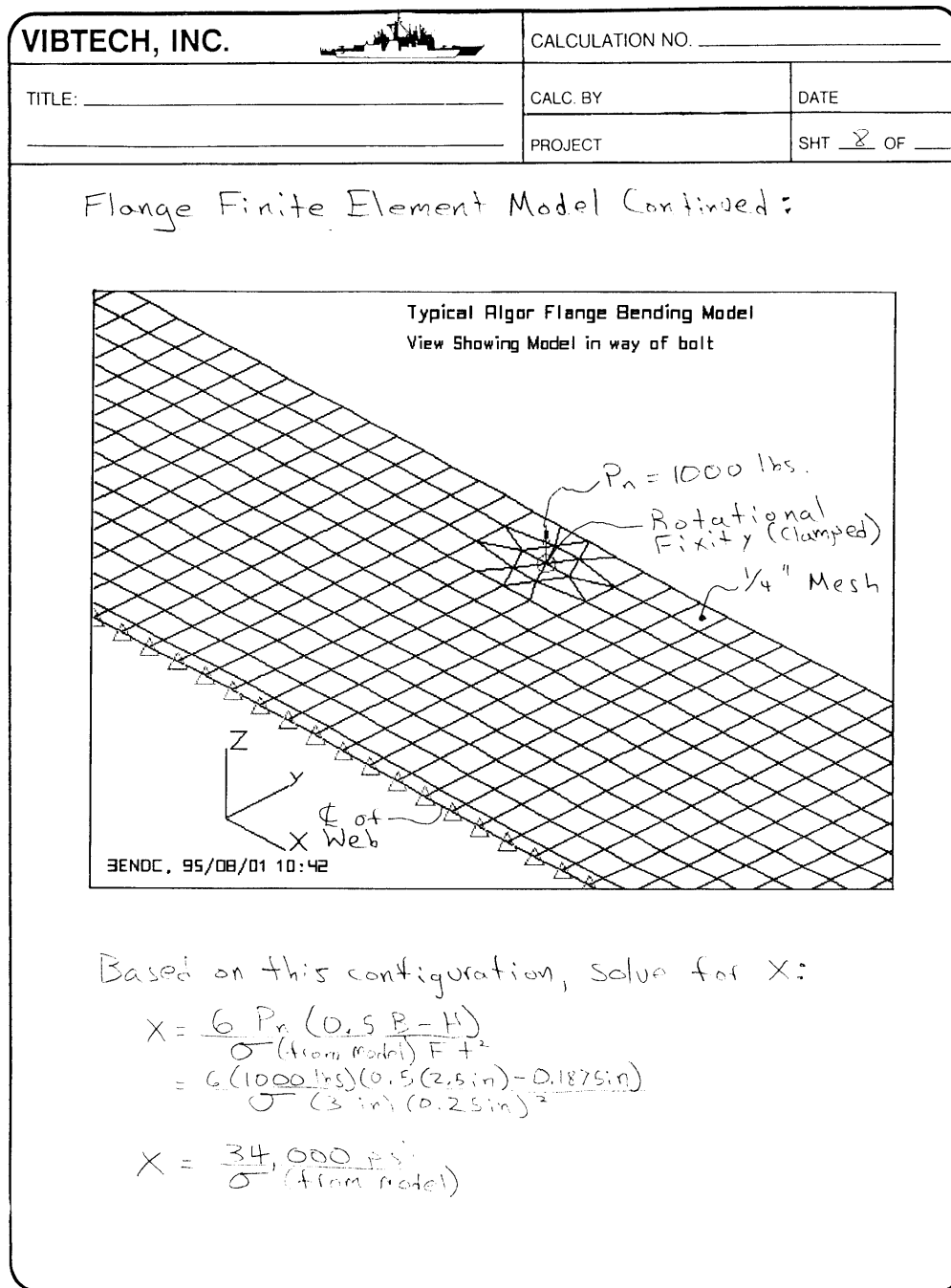


Figure 5-8 — Flange Finite Element Model (Cont'd)

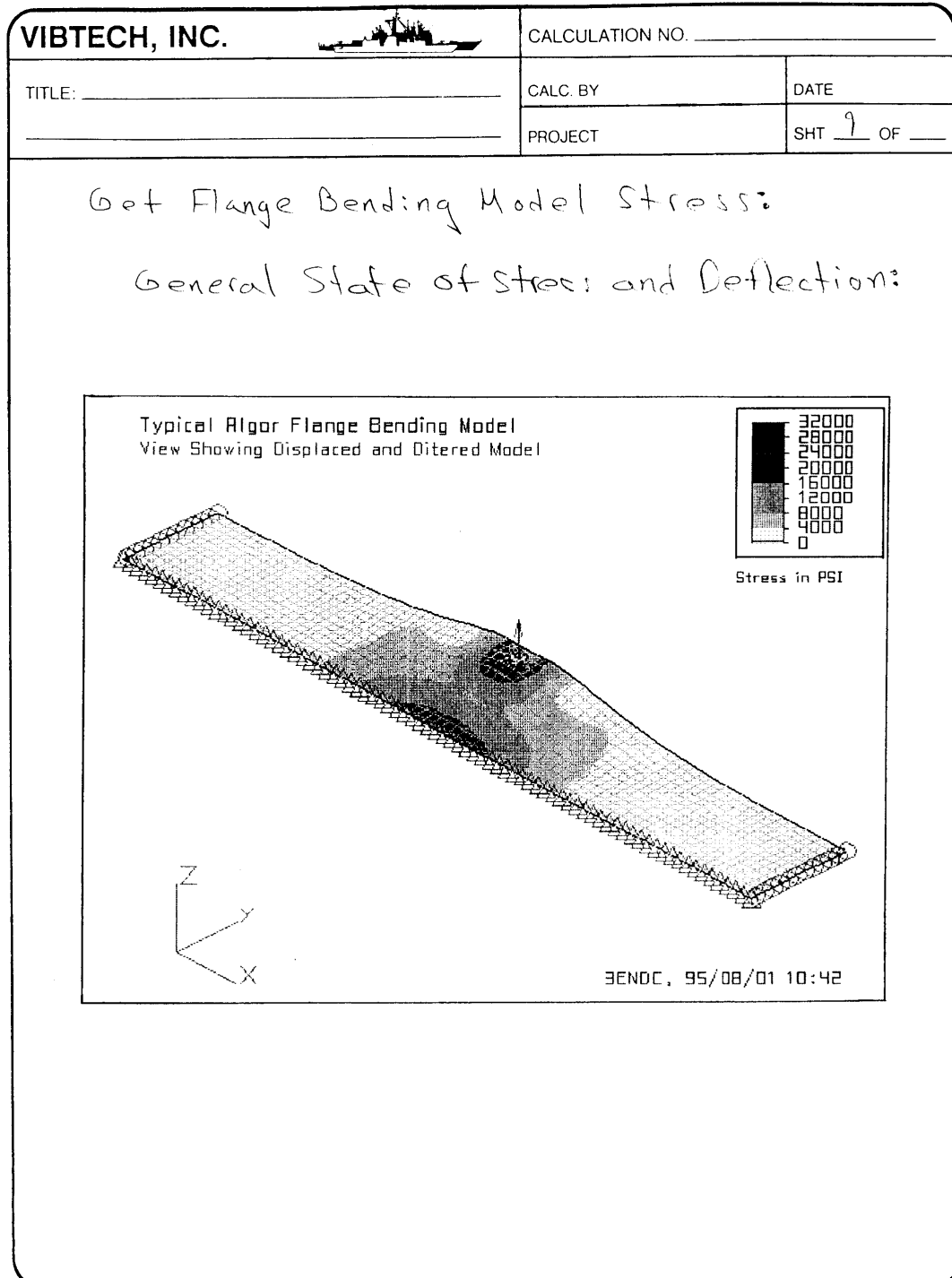


Figure 5-9 — Get Flange Bending Model Stress

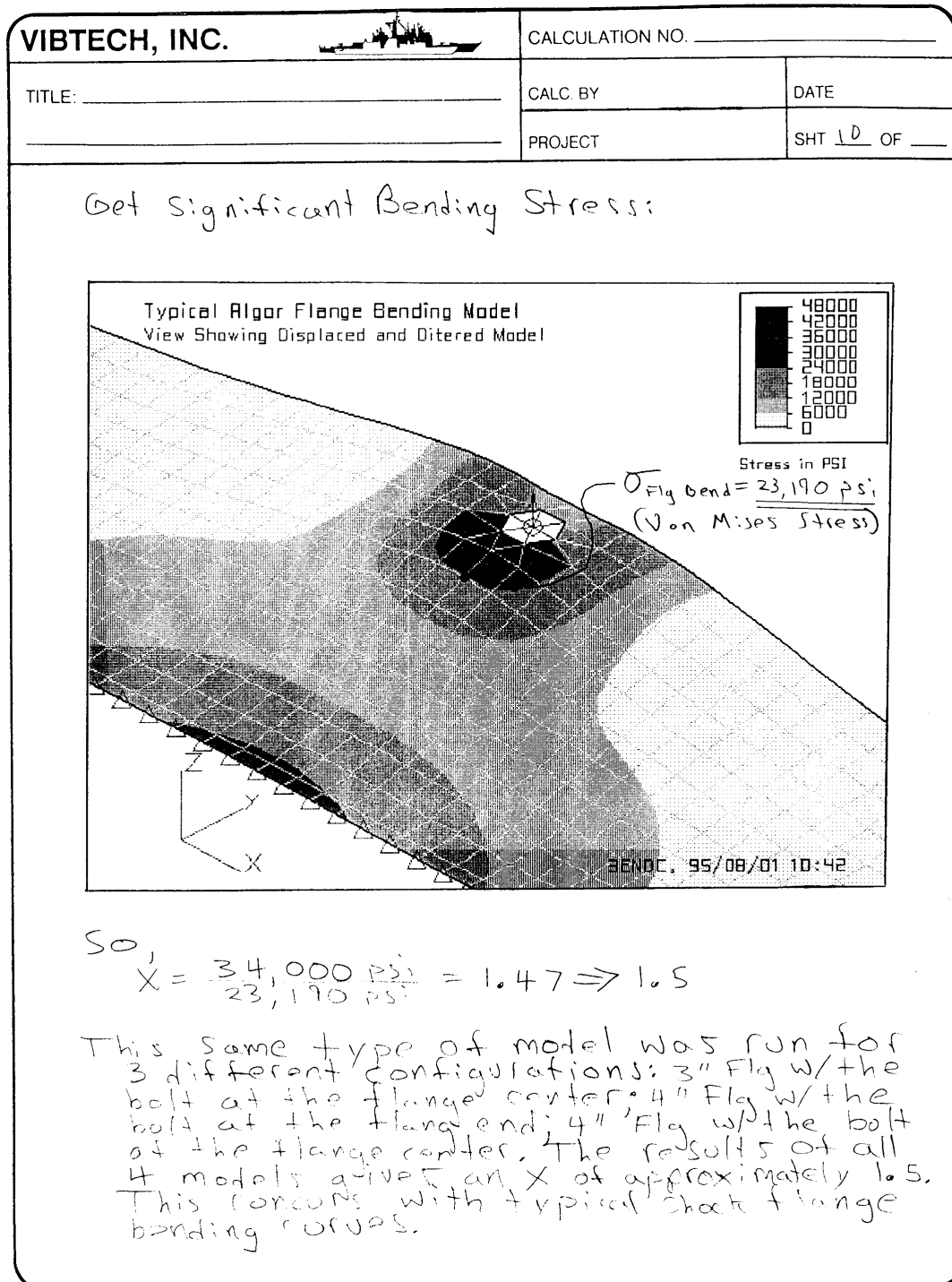



Figure 5-10 — Get Significant Bending Stress

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT AOE-10, TASK 4 SHT <u>11</u> OF ____	

The Flange Bending Formula is Thus:

$$\sigma_{\text{Flg Bnd}} = \frac{6 \cdot P_n (A \cdot B - H)}{1.5 F t^2}$$

where,

- P_n is the axial bolt force
- A is the % of bending moment at the bolt
- B is the distance from ϕ web to ϕ bolt
- H is half of the bolt head width
- F is the flange length
- t is the flange thickness

Figure 5-11 — The Flange Bending Formula is Thus



<p>APPENDIX C — GRILLAGE SPREADSHEET CALCULATION METHOD</p>
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VIBTECH, INC.		CALCULATION NO. _____	
TITLE: <u>Grillage Spreadsheet Calculation Method</u>		CALC. BY <u>SLJ</u>	DATE <u>8/15/95</u>
PROJECT <u>95-040</u>		SHT <u>1</u> OF <u>10</u>	

Example for Spreadsheet Verification:

Accelerations:

$G_x = 0.5$

$G_y = 1.25$

$G_z = 2.5$

Assume Simple Support (pinned-connection)

$L = 40 \text{ in.}$
 $e = 1/2 \text{ of equip. depth}$
 $h = \text{min of } h_+ \text{ and } h_v$
 $e/h = 1.5$

Allowables:

$\sigma_{\text{Axial}} = 0.8 \sigma_{\text{yield}} = 27,200 \text{ psi}$
 $\sigma_{\text{Bearing}} = 0.8 (0.8) \sigma_{\text{yield}} = 21,760 \text{ psi}$
 $\tau = 0.8 (0.6) \sigma_{\text{yield}} = 16,320 \text{ psi}$
 $f_n \geq 12 \text{ ksi}$

Figure 5-1 — Grillage Spreadsheet Calculation Method (Page 1 of 10)

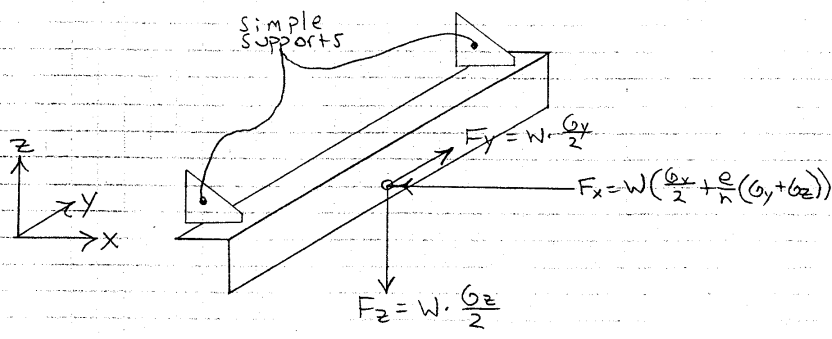
VIBTECH, INC.		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>2</u> OF ____

Angle Properties:

3"x3"x1/4" Angle: $A = 1.4375 \text{ in.}^2$ $Z_{FLG} = 0.577 \text{ in.}^3$
 $I_{FLG} = 1.244 \text{ in.}^4$ $Z_{FLG1} = 1.477 \text{ in.}^3$
 $I_{web} = 1.244 \text{ in.}^4$ $Z_{web} = 0.577 \text{ in.}^3$
 $Z_{web1} = 1.477 \text{ in.}^3$

Given these parameters, find the maximum allowable equipment weight.

Resolve forces on angles and bolts:



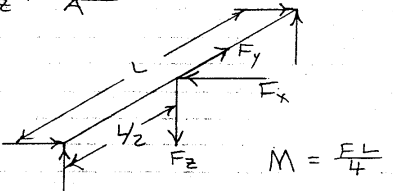
The calculation resolves forces as if there are 4 bolts, but for the purpose of checking stresses it is assumed that there is one bolt at the center of both angles. This conservative assumption captures all conceivable bolting patterns.

Figure 5-2 — Grillage Spreadsheet Calculation Method (Page 2 of 10)

VIBTECH, INC.		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>3</u> OF _____

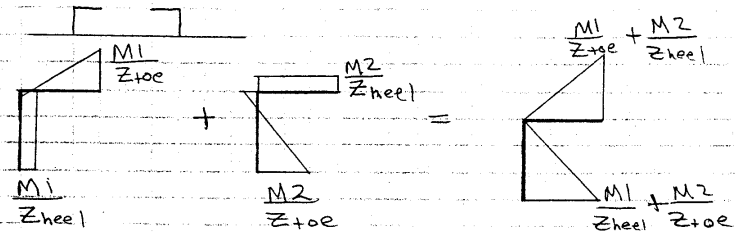
Find allowable weight based on Angle Bending:

$\sigma = \sigma_{bend} + \sigma_{axial} = \frac{M}{Z} + \frac{F_{axial}}{A}$
 2 potential worst locations:
 Flg toe &
 Web toe



$M = \frac{FL}{4}$

Assume worst double bending situation:
Angles toed in.



$$M_z = \frac{FL}{4} = \frac{F_x L}{4} = \frac{W \left(\frac{G_x + e}{h} (G_y + G_z) \right) L}{4} = \frac{W \left(\frac{0.5}{2} + 1.5(1.25 + 2.5) \right) (40 \text{ in})}{4}$$

$$M_z = W(58.75 \text{ in})$$

$$M_y = \frac{FL}{4} = \frac{F_z L}{4} = \frac{W \cdot \frac{G_z}{2} \cdot L}{4} = \frac{W \left(\frac{2.5}{2} \right) (40 \text{ in})}{4}$$

$$M_y = W(12.5 \text{ in})$$

$$\sigma_{flg\ toe} = \frac{M_z}{Z_{flg\ toe}} = \frac{W(58.75 \text{ in})}{0.577 \text{ in}^3} = W(101.8 \frac{\text{in}}{\text{in}^2})$$

$$\sigma_{web\ toe} = \frac{M_z}{Z_{web\ toe}} = \frac{W(58.75 \text{ in})}{1.477 \text{ in}^3} = W(39.78 \frac{\text{in}}{\text{in}^2})$$

$$\sigma_{flg} = \frac{M_y}{Z_{flg}} = \frac{W(12.5 \text{ in})}{0.577 \text{ in}^3} = W(21.66 \frac{\text{in}}{\text{in}^2})$$

$$\sigma_{flg\ heel} = \frac{M_y}{Z_{flg\ heel}} = \frac{W(12.5 \text{ in})}{1.477 \text{ in}^3} = W(8.46 \frac{\text{in}}{\text{in}^2})$$

Figure 5-3 — Grillage Spreadsheet Calculation Method (Page 3 of 10)



VIBTECH, INC.		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>4</u> OF _____

Find double bending allowables:

$$\sigma_{web}^{bend} = \sigma_{web} + \sigma_{F_{H1}} = W(101.8 \frac{1}{in^2}) + W(8.46 \frac{1}{in^2}) = W(110.26 \frac{1}{in^2})$$

$$\sigma_{F_{H2}}^{bend} = \sigma_{F_{H2}} + \sigma_{web}^{bend} = W(21.66 \frac{1}{in^2}) + W(39.78 \frac{1}{in^2}) = W(61.44 \frac{1}{in^2})$$

$\sigma_{web}^{bend} > \sigma_{F_{H2}}^{bend}$, so use σ_{web}^{bend} to figure allowable loads

Find allowable weight based on combined stress:

$$\sigma_{comb} = \sigma_{web}^{bend} + \sigma_{axial}$$

$$\sigma_{axial} = \frac{F_{axial}}{A} = \frac{F_x}{A} = \frac{W \cdot \frac{dy}{dx}}{A} = \frac{W \cdot \frac{1}{2} (1.25)}{1.4375 in^2} = W(0.435 in^2)$$

$$\sigma_{comb} = W(110.26 \frac{1}{in^2}) + W(0.435 in^2) = W(110.7 \frac{1}{in^2})$$


$$\sigma_{comb} \leq \sigma_{allow}$$

$$\sigma_{comb} \leq 27,200 \text{ lbs/in}^2$$

$$W(110.7 \frac{1}{in^2}) \leq 27,200 \text{ lbs/in}^2$$

$$W \leq 246 \text{ lbs}$$

Figure 5-4 — Grillage Spreadsheet Calculation Method (Page 4 of 10)

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>5</u> OF _____

Find allowable weight based on Flange Bending:

$$\sigma = \frac{P(0.8B - H)}{\frac{1}{4} +^2 F} \quad \sim \text{see Appendix B for derivation of this formula}$$

where,

P = force on bolt = $F_x = W(\frac{G_x}{2} + \frac{e}{h}(G_y + G_z))$

B = dist from bolt to web = $3\text{in} - 0.375\text{in} - \frac{0.375}{2}\text{in} = 2.5\text{in}$

H = $\frac{1}{2}$ dia. of the bolt head = 0.21875in for $\frac{1}{4}"$ bolt

t = flange thickness = 0.25in

F = flange length

$$\sigma = \frac{W(\frac{G_x}{2} + \frac{e}{h}(G_y + G_z))(0.8(2.5\text{in}) - 0.21875\text{in})}{\frac{1}{4}(0.25\text{in})^2(3\text{in})}$$

$$= \frac{W(\frac{0.5}{2} + (1.5)(1.25 + 2.5))(0.8(2.5\text{in}) - 0.21875\text{in})}{\frac{1}{4}(0.25\text{in})^2(3\text{in})}$$

$$\sigma = W(223.25 \frac{\text{lb}}{\text{in}^2})$$

$$\sigma \leq \sigma_{\text{allow}}$$

$$\sigma \leq 27,200 \text{ lbs/in}^2$$

$$W(223.25 \frac{\text{lb}}{\text{in}^2}) \leq 27,200 \text{ lbs/in}^2$$

$W \leq 122 \text{ lbs}$

Figure 5-5 — Grillage Spreadsheet Calculation Method (Page 5 of 10)



VIBTECH, INC.		CALCULATION NO. _____	
TITLE: _____	CALC. BY _____	DATE _____	
_____	PROJECT _____	SHT <u>6</u> OF _____	

Find allowable weight based on Bolt Pull-Thru:

$$\tau = \frac{P}{1.5 d \pi t}$$

where

$P = \text{force on bolt} = F_x = W \left(\frac{G_x}{2} + \frac{e}{h} (G_y + G_z) \right)$

$d = \text{bolt nominal diameter} = 0.25 \text{ in.}$

$t = \text{angle thickness} = 0.25 \text{ in.}$

$$\tau = \frac{W \left(\frac{G_x}{2} + \frac{e}{h} (G_y + G_z) \right)}{1.5 (0.25 \text{ in.}) \pi (0.25 \text{ in.})}$$

$$= \frac{W \left(\frac{2.5}{2} + (1.5) (1.25 + 2.5) \right)}{1.5 (0.25 \text{ in.}) \pi (0.25)}$$

$$\tau = W (19.95 \text{ in.}^2)$$


$$\tau \leq \tau_{\text{ALLOW}}$$

$$\tau \leq 16,320 \text{ lbs/in.}^2$$

$$W (19.95 \text{ in.}^2) \leq 16,320 \text{ lbs/in.}^2$$

$W \leq 818 \text{ lbs.}$

Figure 5-6 — Grillage Spreadsheet Calculation Method (Page 6 of 10)

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>7</u> OF _____

Find allowable weight based on Bolt Tear-Out:

$$\tau = \frac{P_p}{2(D - 0.32d) + t}$$

where,

P_p = shear force on bolt = $F_x = W \cdot \frac{G_x}{2}$

D = dist. from ϕ bolt to fly toe = 0.375 in.

d = nominal bolt diameter = 0.25 in.

t = flange thickness = 0.25 in.

$$\tau = \frac{W \cdot \frac{G_x}{2}}{2(0.375 \text{ in} - 0.32(0.25 \text{ in}))(0.25 \text{ in})}$$

$$= \frac{W \cdot \frac{2.3}{2}}{2(0.375 \text{ in} - 0.32(0.25 \text{ in}))(0.25 \text{ in})}$$

$$\tau = W(8.475 \text{ in.})$$


$$\tau \leq \tau_{\text{ALLOW}}$$

$$\tau \leq 16,320 \text{ lbs/in.}^2$$

$$W(8.475 \text{ in.}) \leq 16,320 \text{ lbs/in.}^2$$

$W \leq 1926 \text{ lbs}$

Figure 5-7 — Grillage Spreadsheet Calculation Method (Page 7 of 10)

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>8</u> OF _____

Find allowable weight based on Bolt Bearing:

$$\sigma_{\text{Bear}} = \frac{P_p}{d \cdot t}$$

Where

P_p = Shear force on bolt = $F_x = W \cdot \frac{G_x}{2}$

d = nominal bolt diameter = 0.25 in

t = flange thickness = 0.25 in

$$\sigma_{\text{Bear}} = \frac{W \cdot \frac{G_x}{2}}{(0.25 \text{ in})(0.25 \text{ in})}$$

$$= \frac{W \cdot \frac{2.5}{2}}{(0.25 \text{ in})(0.25 \text{ in})}$$


$$\sigma_{\text{Bear}} = W (20 \frac{1}{\text{in}^2})$$

$$\frac{\sigma_{\text{Bear}}}{\sigma_{\text{Bear}}} \leq \frac{\sigma_{\text{Bear}}^{\text{allow}}}{\sigma_{\text{Bear}}} \leq 21,760 \text{ lbs/in}^2$$

$$W (20 \frac{1}{\text{in}^2}) \leq 21,760 \text{ lbs/in}^2$$

$W \leq 1088 \text{ lbs}$

Figure 5-8 — Grillage Spreadsheet Calculation Method (Page 8 of 10)

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>9</u> OF <u> </u>

Find allowable weight based on Fdn. Natural Frequency:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

Check vibration perpendicular to the plane of the foundation.

$$\frac{1}{k_{\text{Ang}}} = \frac{1}{k_{\text{Bend}}} + \frac{1}{k_{\text{Flg}}} + \frac{1}{k_{\text{Addition}}}$$

But, if it assumed that the equipment is clamped at the bolt, which produces the worst case for flange bending, then torsional rotation does not occur, because it is resisted by the moment produced by the clamping at the bolt. So,

$$\frac{1}{k_{\text{Ang}}} = \frac{1}{k_{\text{Bend}}} + \frac{1}{k_{\text{Flg}}}$$

$$k_{\text{Bend}} = \frac{48EI}{L^3} = \frac{48(30 \times 10^6 \frac{\text{lb}_f \cdot \text{in}^2}{\text{in}})(1.244 \text{ in}^4)}{(40 \text{ in})^3} = 27,990 \frac{\text{lb}_f}{\text{in}}$$

$$k_{\text{Flg}} = \frac{1.6 \times 10^7}{B^2} \cdot k'$$

B = dist. from bolt to ang. heel = 2.5 in.
k' = factor for flange case (see App.) = 1.5 in.

$$k_{\text{Flg}} = \frac{1.6 \times 10^7 (0.25 \text{ in})}{(2.5 \text{ in})^2} (1.5) = 60,000 \frac{\text{lb}_f}{\text{in}}$$

$$\frac{1}{k_{\text{Ang}}} = \frac{1}{27,990 \frac{\text{lb}_f}{\text{in}}} + \frac{1}{60,000 \frac{\text{lb}_f}{\text{in}}} = 5.24 \times 10^{-5} \text{ in/lb}_f$$


$$k_{\text{Ang}} = \frac{1}{5.24 \times 10^{-5} \text{ in/lb}_f} = 19,086 \frac{\text{lb}_f}{\text{in}}$$

$$k_{\text{Perp}} = 2 k_{\text{Ang}} \cdot k_{\text{Ang}} = 2(19,086 \frac{\text{lb}_f}{\text{in}}) = 38,172 \frac{\text{lb}_f}{\text{in}}$$

Compare this stiffness to other modes of vibration. The lowest k will produce the lowest f_n and thus the least allowable weight.

Figure 5-9 — Grillage Spreadsheet Calculation Method (Page 9 of 10)

Figure 5-10 — Grillage Spreadsheet Calculation Method (Page 10 of 10)

VIBTECH, INC. 		CALCULATION NO. _____	
TITLE: _____		CALC. BY _____	DATE _____
_____		PROJECT _____	SHT <u>10</u> OF _____

Allowable weight based on Natural Frequency (continued):

Check vibration parallel to the plane of the fdn.

$$K_{parallel} = 2 \cdot K_{Bend}^{Ang} = 2(27,990 \text{ lbs/in}) = 55,980 \text{ lbs/in.}$$

Check vibration of equipment overturning:

$$\frac{1}{K_{over}} = \frac{1}{0.5 \left(\frac{1}{1.5}\right)^2 \cdot K_{pump}^{Ang}} + \frac{1}{2 \cdot K_{Bend}^{Ang}}$$

$$\frac{1}{K_{over}} = \frac{1}{0.5 (1.5)^2 (19,086 \text{ lbs/in})} + \frac{1}{2(27,990 \text{ lbs/in})} = 2.54 \times 10^{-4} \frac{\text{in.}}{\text{lbs.}}$$

$$K_{over} = 3,943 \text{ lbs/in.}$$

Calculate allowable weight based on lowest K

$$K = \text{Min. of } K_{perp}, K_{parallel} \text{ \& } K_{over} = K_{over} = 3,943 \text{ lbs/in.}$$

$$f_n = 12 \text{ Hz} = \frac{1}{2\pi} \sqrt{\frac{K}{m}}$$

$$m_{allow} = \frac{K}{(12 \text{ Hz} \cdot 2\pi)^2} = \frac{(3,943 \text{ lbs/in})(386 \text{ in/sec}^2)}{(12 \text{ Hz} \cdot 2\pi)^2}$$

$$m_{allow} = 268 \text{ lbs.}$$

$W \leq 268 \text{ lbs}$

Thus, the allowable weight based on flange bending is:

$W \leq 122 \text{ lbs}$



**APPENDIX D — BEND TEST REPORT OF 12" AND 18" PIPE
HANGER PROTOTYPES WITH 3/4" AND 1" DIAMETER WELD
STUDS**



THE TEST

The following bend tests were performed on 12" and 18" long prototype pipe hanger designs. The weld studs tested were the NASSCO 3/4" × 3-1/16" XBL Square Stud #101-111-090 and a prototype 1"×4-1/4" press formed weld stud.

BEND TEST FIXTURE

The studs were welded to 4"×4"×5/8" thick mild steel plates with 4 each 0.540 diameter holes. The plates were then mounted to a 2"×10"×24" plate fixture with 4 each 1/2"×4" grade 2 bolts. Assemblies were clamped and braced under the compression test equipment before each test. Pipe hangers were attached to the studs with 2 each 3/8" grade 2 bolts.

TEST OBSERVATIONS AND COMMENTS

TEST NO. 1

At approximately 325 lbs., the 3/4" stud started to yield at about 0.400" deflection. Total load at 1.500" deflection was 405 lbs. The pipe hanger did not yield.

TEST NO. 2

At approximately 160 lbs., the 3/4" stud started to yield at about 0.600" deflection. Total hanger deflection after load was released was about 0.250".

TEST NOS. 3 AND 4

The 1" diameter weld stud did not bend. Maximum load was achieved at about 1.500" deflection in both tests.

TEST NO. 5

Significant additional strength was obtained with the addition of a side brace. Over 500 lbs. Was applied before measuring 0.100" of deflection. The 3/4" diameter weld stud did not yield. A 1/2"×1" CFL mild steel weld stud was used to fasten the "L" bracket to the test plate. The threaded stud was located 16" on center from the center of the hanger.

TEST NO. 6

The 1" diameter stud did not yield. Higher load values could be obtained with modification to the clamp around the top at the hanger to keep it from sliding. Similar load values would be expected from a 3/4" diameter weld stud. A 1/2"×1 CFL mild steel weld stud was used to fasten the "L" bracket to the test plate. The threaded stud was located 12" on center from the center of the hanger.



TEST NO. 7

The goal post was connected at the top with a 3/8"×3"×18" steel plate with two 5/8"×2" bolts. Both weld studs started to yield at about 1150 lbs. with 0.600" deflection.

TEST NO. 8

The goal post was connected at the top with a 3/8"×3"×18" steel plate with two 5/8"×2" bolts. The 1" diameter weld studs did not yield.